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Development of a novel portable test device to measure the tribological behaviour of shoe interactions with tennis courts

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Abstract

The interaction between tennis player and court is a complex problem determined by parameters that can be broken down as: the range of player movements and loading (e.g. push-off and sliding); a variety of surfaces (e.g. clay, acrylic and grass) and different shoe properties (e.g. sole material and tread geometry). These combinations generate different levels of friction that relate to both playing performance and safety. This paper presents the observations, findings and design methodology of a mechanical portable device to improve the understanding of tennis shoe-court interactions and allow courts to be measured and monitored.
Case studies of biomechanical player testing (kinetics and kinematics) and examination of how the tribological mechanisms change with different parameters (e.g. shoe orientation, contact area, roughness, shoe temperature), were considered in the design of a device capable of simulating the key aspects of the player-court interaction.
Eventually, this portable device will be an integral part of a standard test protocol for the International Tennis Federation, to quickly assess courts around the world and aid in the provision of high quality courts for elite use.

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Keywords: Tennis; shoe-surface; friction; tribology; mechanical test device

1. Introduction

Establishing the characteristics of player-court interaction in tennis is a key challenge. A crucial element in tennis is that it is played on different surfaces, where the main factor between the shoe and the surface is the level of friction [1]. The governing body of tennis (International Tennis Federation) is responsible for setting the rules and maintaining the standards of the sport, and therefore needs a system to quickly assess courts around the world and rate them according to expected performance during player interaction. This complex interaction is primarily determined by the player, surface and shoe. The interaction between these parameters can be broken down further as: the range of player movements (e.g. push-off and sliding), on a variety of surfaces (e.g. clay, acrylic and grass) and different shoes properties (e.g. material and tread geometry). These combinations generate different levels of friction that relate to both playing performance and safety.

The aim of this paper is to present the observations, findings and design methodology of a mechanical portable device to improve the understanding of tennis shoe-court interactions and allow courts to be measured and monitored.

Nomenclature	
COF, COT	Coefficient of friction, coefficient of traction
CC, HC	Clay court, hard court
DCOF	Dynamic coefficient of friction

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DMTA	Dynamic mechanical thermal analysis
F_z	Vertical component of Ground Reaction Force (N)
ITF	International Tennis Federation
LVDT	Linear variable differential transformer
P_{peak}	Pressure peak (kPa)
Ra	Mean roughness value (μm)
SCOF	Static coefficient of friction
SD	Standard deviation
TS1, TS2	Test shoe slider 1 and 2
TSSTv1	Tennis shoe-surface test version 1

2. Biomechanical studies

In order to provide the boundary conditions for the mechanical test rig, a number of tennis biomechanical studies were analysed to collate relevant kinetics and kinematics data from tennis players performing typical tennis movements on different surfaces. Several lab and field studies [2-5], shown in Table 1, have reported human loading conditions during dynamic tennis movements on hard and clay courts. However, due to the magnitude of the forces, the challenge relies on replicating them on a tennis court with a light, portable device. However, knowledge in-shoe pressure data [6-8] opens the possibility to develop a field device that replicates levels of pressure, rather than force. Table 1 exhibits a summary of the reported values of different studies of foot peak pressures on clay and hard courts during running forehand, side jump, sliding, and baseline serve and volley movements.

Table 1. Summarised F_z and P_{peak} (SD) data of different movements on two surfaces (references cited for each).

	F_z		P_{peak}	
Movement	**HC**	**CC**	**HC**	**CC**
Forehand	1469 (583) [2] 1681 (484) [3] 1936 (484) [4]	1351 (379) [2] 1829 (393) [3]	417 (77) [6] 512 (85) [6]	379 (74) [6] 456 (112) [6]
Side Jump	1244 (100) [3]	1317 (82) [3]	428 (71) [6]	351 (73) [6]
Turn	1432 (593) [5]	1319 (500) [5]	-	-
Stop	1833 (646) [5]	1680 (713) [5]	-	-
Baseline play	-	-	381 (69) [7]	404 (137) [7]
Sliding	-	-	-	200 – 220 [8]

3. Tribological mechanisms

Tennis shoes outsoles are made from viscoelastic rubber. When this rubber is compressed against a hard tennis surface with some roughness, there is an interaction between their asperities, and hence a friction. There is some evidence of test methodologies utilised to measure the friction between a rubber foot and a tennis court. A pendulum test (Slip resistance test, ITF CS 02/01), and The Crab III devices have been previously used to examine translational surface friction on acrylic tennis courts [9].

Although translational friction has been measured with the equipment mentioned, there are various parameters that need to be considered during the design of new test methodologies. During typical dynamic tennis movements (e.g. push-off, running, sliding), the friction between the viscoelastic material and a hard substrate is ruled by different parameters such as the normal load, surface roughness, shoe orientation and temperature, and contact area [10-14]. These affect the contact between the asperities of the two materials, and hence, the adhesional and hysteretic components of the friction. Fundamental friction mechanisms were examined by two initial studies that formed the basis for further device development:

In the first study [10], the effect of a shoe normal force applied to a surface on friction was studied. Via a laboratory based test rig, it was found that friction is dependent on the normal force. As the normal force applied to a surface increases, the COF (referred to in this study as "coefficient of traction", COT) decreases and a power relationship can be fitted as shown in Figure 1(a).

The second study [11] showed that relationships between roughness and dynamic friction were found to be also dependent on the normal load. Under high normal loads (e.g. 1000 N), the friction decreases with roughness, reaches a minimum and then increases as the roughness increases. The opposite behaviour is observed under low normal loads (e.g. 500 N), and the trend is for friction force to increase with roughness, reach a maximum and then decrease as the roughness increases.

Another study, [12] examined the effect of shoe orientation on the friction generated by the shoe-surface interface. Friction tests were performed on an acrylic hard court tennis surface. A forefoot segment of a commercial tennis shoe was pressed and then made to slide, when mounted in four orientations, 0, 30, 60 and 90°, relative to the sliding direction. Strong and significant relationships were found between normal force and dynamic friction force showing differences between the orientations shown in Figure 1(b).

Shoe outsole temperature is another factor that affects the friction. In a further study [13] it was found, based on DMTA and hardness data, that during a slide on a hard court, the rubber sole material tends to reduce its damping and hardness as the temperature increases. As a consequence, it will deform more, increasing contact area and therefore the level of friction which will induce heat generation and a further increase in temperature.

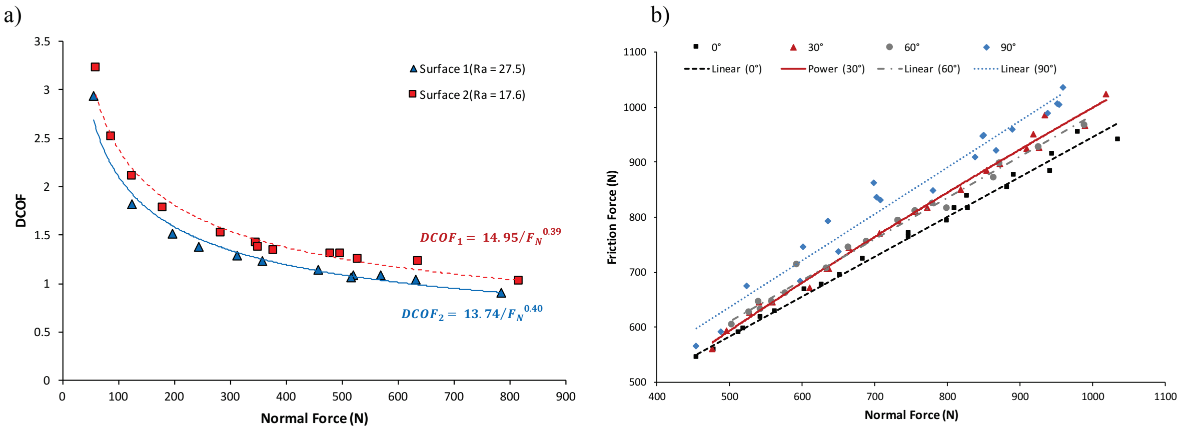


Fig. 1. (a) Normal force against mean coefficient of traction (adapted from [10]); (b) Plot of the normal force against traction force for each shoe orientation (adapted from [12]).

The effect of shoe-surface contact area and pressure at different vertical loads was also investigated [14]. Three sizes of the same design of commercially available hard court tennis shoes were used in the study. The contact areas of a forefoot segment of each shoe were measured when subjected to loads ranging from 600 to 1600N in intervals of 200 N; allowing conversion of teste parameters to average applied pressure. Additionally, friction testing was carried out, allowing the combination of data based on applied pressure, with a combination of different areas and vertical loads. All three shoes were found to show a similar trend, regardless of size.

4. Development and validation of the portable test device

The aim was to create a mechanical test device to conduct repeatable and reliable shoe friction tests on a range of tennis surfaces. In order to satisfy the needs from the ITF, a number of design requirements were defined, with the three main ones being:

- Portable and light design to transport around the world.
- Representative of match play conditions.
- Interchangeable test shoe with representative material tennis shoe.

Design and development stages were performed based on the platform of understanding and observations summarised in sections 2 and 3. As suggested in previous studies [15, 16] mechanical tests should ideally replicate the materials and loading of specific human–shoe–surface interactions. However, due to the magnitudes of the vertical forces generated during complex dynamic movements (Table 1), the replication of the actual biomechanical loading using portable equipment is a challenge. Therefore, it was decided to replicate real play conditions by matching *in-sole peak pressures* (Table 1), an approach that had been validated in part by the previous pilot study on pressure and friction [14]. Pressures could be achieved using lower vertical loads by reducing the contact area of the test shoe. The protocol of this portable device, similar in concept to other friction test devices [16], was to measure the limiting friction generated when a shear force was gradually increased against a test shoe under a constant vertical load.

Based on the design requirements, a first prototype device (TSSTv1) was developed at the University of Sheffield (Fig. 3(a)). The device consists of three main components: a sled, a pneumatic ram and a test shoe slider. Compact dimensions (800 × 400 × 150 mm) in use and an approximate weight of 10 kg without the applied weight, makes the device relatively light and portable.

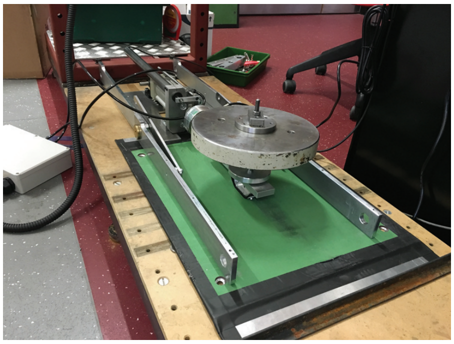
First, a test shoe slider (Fig. 2b) is attached onto the sled with a number of weights mounted on top of the sled, to replicate the desired shoe pressure, as previously calibrated. A solenoid valve is then activated, opening the pneumatic cylinder providing a horizontal force to drive the sled. The horizontal force increases until sliding of the shoe test slider is initiated. The maximum sliding length is 100 mm. A load cell and a LVDT in the horizontal direction provide the measurements necessary to define the friction provided. A data acquisition device (NI9174) with synchronised and signal-conditioning modules (NI9237 and NI9215) samples the signals from the load cell and LVDT. These voltage signals, sampled at 1600 Hz, are transformed into force and displacement data and displayed in real time using LabView (version 14 National Instruments).

The test shoe slider, shown in Fig. 2(b), was designed to mount different test rubbers. The dimensions of the slider are 63.5 × 31 × 17 mm with a flat area of 31 × 31 mm. The test rubber is glued on the bottom part of the slider and mechanically secured with four screws. A commercial Nitrile Butadiene Rubber (N70) was chosen for initial testing, due to its similarities in comparison with the rubber compound of a commercial tennis shoe [17] as shown in Table 2. Validation and comparison of this rubber against an actual tennis shoe outsole is part of another study [18], where the the effects of different tread patterns were also investigated.

Table 2. Comparison of the mechanical properties of the N70 rubber and a typical tennis shoe outsole

Mechanical Properties	**N70 Nitrile Butadiene Rubber (NBR)**	**Tennis shoe outsole** [16]
Shore Hardness	71	68 - 72
Tensile strength (MPa)	14	13 – 15
Elongation at break (%)	385	350 – 500 %

a)



b)

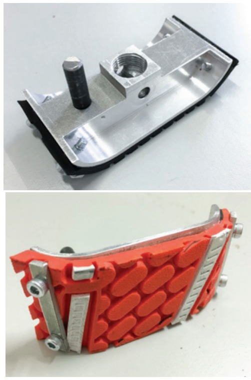


Fig. 2. (a) TSSTv1 first prototype with a 10kg weight shown in the lab; (b) Test shoe sliders.

4.1. Validation and results

As a first validation, a comparison of friction measurements was performed between the TSSTv1 and a lab-based shoe friction device [16], using one hard court surface sample (Ra = 14 µm). Two forefoot segments of a commercially available *all court* tennis shoe (Fig. 3b) of the same design but different size (EU sizes 31 and 39) were tested on the surface with the lab–based device. The vertical loads ranged from 600 – 1600 N in intervals of 200 N. Additionally, with the TSSTv1 portable test, two test shoe sliders were used. One slider, "TS1", used flat Nitrile Butadiene rubber whilst the other, "TS2" was made from a section of shoe of the same design as used with the lab-based device (Fig. 3(b)). Both sliders were tested over the same surface with a vertical load ranging from 100 – 400 N in intervals of 100 N. The test orientation for both samples was of approximately 50º in relation to horizontal movement (Fig. 3(b)). Based on the displacement data, the test shoe slider speed was determined to range from 0.15 to 0.45 m/s. Ambient temperature was monitored throughout the testing. Additionally, after 5 tests with each test shoe slider, these were allowed to cool down from any possible increment of outsole temperature.

Subsequently, the shoe-surface contact area of the forefoot segments and the test shoe sliders was calculated using an ink protocol described in [14]. The SCOF was calculated for both data sets, using an existing analysis protocol that considers the peak measured friction force before sliding was initiated [16]. The measured contact areas increased with increased vertical load for both shoe sizes and the test shoe slider, in agreement with previous experiments [14]. Figure 3(a) shows the results for SCOF plotted against average applied pressure (assumed to be the average pressure experienced by the shoe immediately before the onset of sliding). All the tests showed the same general pattern of behaviour as the previous study [14], with SCOF decreasing with increased applied pressure. SCOF data for both sizes of the shoe test segment and slider TS2 overlapped in the pressure range 300-350 kPa. Allowing for a sensible degree of extrapolation, it would be expected that similar friction behaviour would also be found over an extended pressure range 300 – 500 kPA, a range covering that measured in previous biomechanical studies of actual players (see Table 1). However, the friction data obtained using the flat NB rubber slider (TS1) indicated slightly different behaviour.

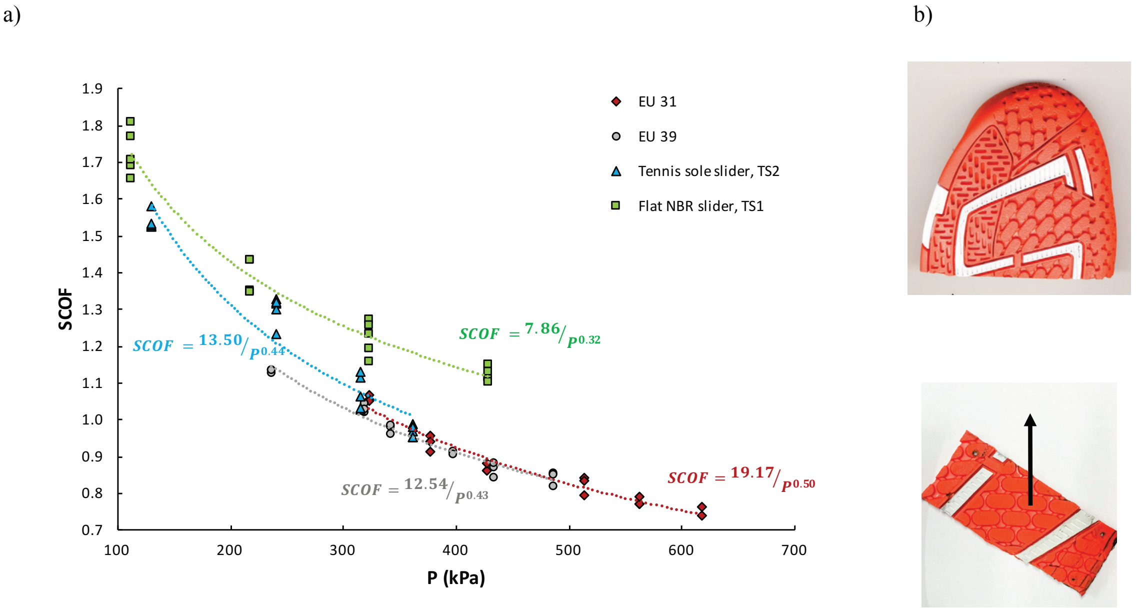


Fig. 3. (a) Plot of the average applied pressure against SCOF for each shoe and test slider with fitting equations; (b) Forefoot segment (top) and TS2 sample (bottom). Arrow shows the 0º line with horizontal movement and angle is increased by rotating clockwise

5. Discussions

Despite many years of research, the opportunity to establish the characteristics of player-court interaction in tennis with a realistic portable device has been a challenge. The development and design of the TSSTv1 prototype has demonstrated, through initial testing, potential to be able to replicate biomechanical tennis conditions and measure the friction generated by a shoe in contact with a surface. The main principle of this device is to be capable of simulating the key aspects of the player-court interaction with a representative rubber material. This has been achieved by matching player insole peak pressures with a small shoe test area and lower vertical loads applied, instead of applying higher vertical loads. The friction results presented in Fig. 3(a) have confirmed the findings of a previous study [14] and opens new possibilities of field testing, as to apply pressures representative to match-play conditions using portable devices with a relative small size of test slider.

Regarding the comparison between a tennis shoe tread sample (TS2) and a flat NBR slider with similar properties (TS1), it is clear that sole geometry (e.g. presence of a tread pattern) has a significant effect on friction behaviour. The differences between these two sliders tested could be due to the different adhesional and hysteretic friction mechanisms generated. Further work is continuing to assess the effects of different tread patterns and the results will feed into the final development stage [18].

As mentioned in the tribological mechanisms section, previous studies have demonstrated that surface roughness and shoe outsole temperature are factors that affects the friction between the rubber sole and hard court surfaces. It is then necessary to complement the obtained friction value with roughness measurements of the surface tested. In addition, the temperature of the surface and the rubber of the test shoe slider needs to be monitored to avoid differences in the friction measured.

Another factor that needs to be considered is the level of the slider wear. For the final design of a portable device, the slider needs to be robust enough to cope with repeated testing and not wear to such a degree that repeatability is then affected. It also needs to be simple enough to allow cost effective manufacture and sourcing for testing in the future. A compromise may need to be found between a slider material and tread pattern that is similar to existing tennis shoes, yet performs consistently and is relatively easy to acquire replacements for, as typical tennis shoes are made to resist the abrasion of rough surfaces, however with a commercial rubber, it is important to measure and evaluate the wear after specific number of tests, in order to be replaced with a new one.

Dynamic friction data could be obtained from the data collected for this study, however, this article focuses only on the comparison and validation of SCOF, as the speeds of the test shoe slider are below typical maximum speeds in tennis, which are close to 4 m/s [19]. Further improvements are necessary to achieve higher speeds, and once implemented, additional studies will be performed in order to compare the dynamic friction. Although the initial validation testing shows promise, the measurements presented here were performed only over one hard court tennis surface. Further work will consider hardcourts of different roughness and other surfaces such as clay and grass, where the tribological mechanisms are very different.

Further validations of TSSTv1 against other mechanical devices also need to be carried out and we also consider it relevant to compare results from this device against player perception of different surfaces [20].

Finally, some mechanical improvements could be made to the prototype version to improve easy of use, and wider field testing over a range of tennis courts can be carried out in-situ, with the objective of assessing and validating the device for actual use.

6. Conclusion

In summary, although further mechanical improvements and validation to the TSSTv1 portable device need to be carried out, the approach of using a relative small shoe test area with a reduced vertical load to match player insole pressures has shown promise to replicate real play conditions and measure the shoe-surface friction performance. This novel method of combining experimental testing based on real biomechanical data and real test shoe material open new possibilities for field testing, and a better understanding of the friction provided by different tennis court designs and systems. With further development, this portable device could be an integral part of a standard test protocol for the ITF, to quickly assess courts around the world and aid in the provision of high quality courts for elite use. This approach could then be adopted in other areas and improve the quality of tennis surfaces for all.

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References

1. Nigg B, Segesser B. The influence of playing surfaces on the load on the locomotor system and on football and tennis injuries. Sports Med. 1988; 5: p. 375-385.
2. Damm L, Clarke J, Carré M, Dixon S. Biomechanical and mechanical testing of non-sliding and sliding tennis surfaces. Footwear Sci. 2013; 5(1): p. S117-S118.
3. Damm L, Low D, Richardson A, Clarke J, Carré M, Dixon S. The effects of surface traction characteristics on frictional demand and kinematics in tennis. Sports Biomech. 2013; 12: p. 389-402.
4. Stiles VH, Dixon SJ. The influence of different playing surfaces on the biomechanics of a tennis running forehand foot plant. J of App Biomech. 2006; 22: p. 14-24.
5. Carré MJ, Clarke JD, Damm L, Dixon S. Friction at the tennis shoe-court interface: how biomechanically informed lab-based testing can enhance understanding. Proc Eng. 2014; 72: p. 883-888.
6. Damm L, Starbuck C, Stocker N, Clarke J, Carré M, Dixon S. Shoe-surface friction in tennis: influence on plantar pressure and implications for injury. Footwear Sci. 2014; 6(3): p. 155-164.
7. Girard O, Eicher F, Fourchet F, Micallef JP, Millet GP. Effects of the playing surface on plantar pressures and potential injuries in tennis. Br J Sports Med. 2007; 41(11): p. 733–738.
8. Bloch O, Potthast W, Bruggemann GP. Pressure distribution during sliding on tennis clay court. In Symp On Foot Biomech; 1999; Canmore, Canada: Footwear Biomechanics. p. 26/27.
9. Miller, S., & Capel-Davies, J. (2006, April 26). An initial ITF study on perfor- mance standards for tennis court surfaces. Paper presented at the SportSurf 2nd Workshop, Cranfield University.
10. Clarke J, Carré M, Richardson A, Yang Z, Damm L, Dixon S. Understanding the traction of tennis surfaces. Proc Eng. 2011; 13: p. 402-408.
11. Clarke J, Carré M, Damm L, Dixon S. The influence of surface characteristics on the tribological interactions at the shoe-surface interface in tennis. Proc Eng. 2012; 34: p. 866-871.
12. Ura D, Clarke J, Carré M. Effect of shoe orientation on shoe-surface traction in tennis. Footwear Sci. 2013; 5(1): p. S86-S87.
13. Ura D, Conway J, Booth J, Carré M. Tennis shoe outsole temperature changes during hard court sliding and their effects on friction behaviour. Proc Eng. 2015; 112: p. 290-295.
14. Ura D, Domínguez-Caballero J, Carré M. Tennis shoe–court interactions: examining relationships between contact area, pressure and available friction. Footwear Sci. 2015; 7(1): p. s87-s89.
15. Dixon S, Batt ME, Collop AC. Artificial playing surfaces research: A review of medical, engineering and biomechanical aspects. Int J of Sports Med. 1999; 20: p. 209-218.
16. Clarke J, Carré M, Damm L, Dixon S. The development of an apparatus to understand the traction developed at the shoe-surface interface in tennis. Proc of the Inst of Mech Eng, Part P: J of Sports Eng and Tech. 2013; 227(3): p. 149-160.
17. Yu SC, Schiller D, Bergmann M, inventors; Outsole for an article of footwear. United States patent US7765720B2. 2010 Aug 3.
18. Goff JE, Ura D, Carré M. Parametric study of simulated tennis shoe treads. Proc Eng. 2016 (in press).
19. Ura D, Carré MJ, Charlton H, Capel-Davies J, Miller S, Almenara MS, et al. Influence of Clay Properties on Shoe-kinematics and Friction During Tennis Movements. Procedia Engineering. 2014;72:889-94.
20. Starbuck C, Damm L, Clarke J, Carré M, Capel-Davis J, Miller S, et al. The influence of tennis court surfaces on player perceptions and biomechanical response. J Sports Sci. 2015 Dec; 23: p. 1-10.